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DISADVANTAGES OF SINGLE PHASE LINES ON PIONEER RURAL LINES

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Disadvantages of single phase lines on pioneer rural lines -

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1. Unbalance due to single-phase loads

The primary distribution in many countries has been accomplished by means of single-phase lines, with the recommendation, - considering the possibility of a future substitution for a three-phase line - that the project should be designed, so as to permit, for economical reasons, later on, a good use of the initial installations.

With a balanced three-phase load there are no serious problems of regulation, since this may be satisfied with the use of voltage regulators, the currents as well as the power, being always balanced.

Some remarks of substantial technical importance, should however be made aiming at the use of single-phase lines tapped off three-phase systems. In the strict sense of equivalence it is not possible to transform polyphase into single-phase power employing only transformers. The reason is that, single-phase power is characterised by the supply of "pulsating" energy, i.e., it varies periodically from zero to the maximum value; whereas a balanced polyphase power is characterised by a continuous supply of energy at a constant value. It is then evident that the transformation of a continuous supply of energy at a constant value, into a pulsating form of energy, or vice-versa, is not possible without provision for the kinetic storage and restitution of power.

It is clear therefore, that it is a waste of time to try to solve the problem employing special connections or

or arrangements in the transformers. Innumerable tentatives have been made, with results, which may be considered reasonable, having in view a balanced distribution of current when connecting single-phase loads to a polyphase system. But balanced "currents" do not signify balanced energy, and consequently do not mean smaller losses in the windings of the generator.

The resulting reactions and the effects of the unbalance of these currents lagging or leading have precisely the same effect in the energy-generating system as the single-phase load which causes the unbalance of the currents.

A correct method for obtaining, in the most favourable electrical conditions single-phase power from a three-phase system, is the use of a motor-generator set. In such a case a three-phase motor drives a single-phase generator and the single-phase load is obtained by the transformation of the electrical energy. In this method, we have complete "electrical" independence between the three-phase and the single-phase systems; it is therefore the ideal method, although more expensive.

2. Economical aspects of distribution lines

a) Cost of equipment of the primary line - Considering the first cost alone, and the investment for a given amount of power, a three-phase system is about 80% cheaper than the corresponding single-phase system. Such a conclusion may be easily reached by an identical analysis, as shown in item (b), relative to a secondary line.

This conclusion may not be valid if the conductor size dictated by considerations of regulation and efficiency is smaller than that dictated by mechanical considerations, which is not normally the case.

Examining the abacus, shown in the publication "Distribution Data Book", of the General Electric, it may be seen that, with a wire ACSR nº 4 of Copper-nº 6, a load of 500 kW, power factor 0,9 inductive, may be transmitted with a regulation of 5% over a distance of 12 km (7,5 miles) in a three-phase system at 13,8 kW.

Whereas, the single-phase transmission of this same amount of power (500 kW) at the same power factor and for the same efficiency and regulation, would be possible only for a distance not exceeding 6 km.

Wherefrom we can conclude that, only fro very small distances may the single-phase system compare favourably with the three-phase system for rural distribution; but the small distances are uncommon in such application.

There are, however, some cases where the single-phase system may appear to result cheaper than the three-phase system. The first is when a common neutral wire is used for both the high, and low voltage sides when they run along the same route.

But, besides this being rarely the case, and an unadvisable practice for many reasons, the saving is problematical

because :

- the neutral wire is quite unnecessary on the primary three-phase line; therefore it cannot be said that there is a saving of one neutral wire.

- this solid connection of the two neutrals over long distances, and varying conditions or facilities for proper grounding and its proper maintenance, may turn out to be a very expensive economy.

The second is the possibility of using the earth as a return for the single-phase lines, which is also not advisable as has been proved by technical investigation and experience.

b) Cost of secondary distribution -

Let V = voltage between phases, and I = line current then,

$$P = V I_1 . \cos \phi \qquad \text{(single-phase)}$$

$$P = V\sqrt{3} . V I_3 . \cos \phi \qquad \text{(three-phase)}$$

$$\therefore I_1 = \sqrt{3}\ I_3$$

For equal losses : $2 R_1 I_1^2 = 3 R_3 I_3^2$

$$R_1/R_3 = 3 I3^2/2 I_1^2 = 1/2$$

if the respective conductor cross sections are a_1 and a_3, we have :

$$R_1/R_3 = 1/2 = a_3/a_1$$

and for equal distances of transmission the weights of copper are $Cu_{(3)}/Cu_{(1)} = 3/4$, which results in a 25% economy in cost of conductor for the three-phase case.

3. Utilization and manufacture of single-phase equipment

There is no objection to the connection of single-phase low power (mostly domestic) appliances to the single-phase lines; this must however be avoided for larger power equipment of 10 HP (7,5 kW), and upwards, which should always be three-phase.

Let us consider in first place the equipments used for disconnection and protection, and afterwards those for consumption.

In order that the illustration should be convincing we hall compare a single-phase equipment with a three-phase equipment of the same power.

Taking, for instance, for the single-phase case, 15 kW at 220 V, the current will be 68 A; and for three-phase at 380 V, the current will be 23 A.

a) Circuit breakers

The single-hase circuit breaker needs two main contacts for conduct

conducting and interrupting the current of 68 A; whereas the three-phase one needs three contacts for 23 A. The energy dissipated in the contacts is inversally proportional to their area, or cross section; while their capacity of dissipation is proportional to their external surface. Consequently the weight of the contacts is approximately proportional to the current.

As the ratio between the number of contacts for single-phase and three-phase circuit breaker is 2/3, the ratio between the weights of each contact for single-phase and three--phase being 3, the ratio between the total weight of the single-phase and three-phase circuit breaker contacts is 2.

It results from this that the switching mechanism, for controlling the circuit and the operating springs (if any) have to be proportionally larger for the single-phase, because the volume of the component parts is approximately proportional to the current, for the sizes under consideration.

Consequently the circuit breaker for single-phase will have twice the weight and volume of that for three-phase; probably not quite so much, due to the diminution of space for insulation, since there are only two contacts, instead of three. A closer estimate might give a value of 1.5 or thereabout for this ratio.

With respect to the cost, as only the weight and wages affect it, the volume is of no importance. The labour costs will be only slightly greater for the three-phase, since the erection work requires a greater number of operations, but the smaller and lighter equipment can be easier manipulated. As a first approximation the total cost might be split as follows:

Material	45%
Wages	30%
General expenses	10%
Interest on the investment	15%

Taking the unit-value for the single-phase, and admitting that the labour for single-phase is only 80% of three--phase, we shall have :

	Single-phase	Three-phase
Material	45	30
Wages	30	37,5
General expenses	10	9
Interest on the investment	15	13,5
	100%	90%

That is to say, for the same power, the three--phase C.B. may cost only 90% of the price of the single-phase C.B. and occupyes only 67% of the space which is also of great economical importance.

b) Consumer's equipment

Relative to the consumers of energy we may point out some typical equipments, which represent important classes, i.e. :

- lighting equipment
- heating equipment
- motors

Lighting equipment, even if connected to three--phase systems, is always single-phase and therefore does not affect this discussion.

i) Heating equipment - Heating equipment can be single-phase or three-phase.

In the resistance type, the heat production is proportional to the square of the current, to the resistance of one element and to the number of the elements.

Suppose we have a three-phase heater, delta connected to the three-phase line, and a single-phase heater of equal power connected between phase and neutral of the same line.

Then, it can be shown that, in these conditions, the resistance of each phase element of the three-phase heater, is equal to 9 x resistance of the single-phase heater.

That is to say, each one of the three elements of the three-phase heater, having the same length as that of the single-phase heater, will have one ninth of its weight, consequently the total weight of the elements of the three-phase heater, will be one third of the weight of the elements of the single-phase heater.

The material of which these elements are made is of high cost; this is the reason why the single-phase heater is of considerably higher cost than the three-phase one; approximately, in the ratio of 2:1.

ii) Motors - Of all consuming devices unusually encountered in rural electrification, the squirred cage induction motor is without doubt, the one for which three-phase current is most suitable.

This because in the single-phase motor we cannot produce an even and symetrical revolving field which is intrinsec property of the three-phase windings, this resulting in considerable waste of frame space, only occupied by starting windings, which are not effective for continuous power development.

This naturally makes the single-phase motor more expensive, besides the complication of starting equipment.

The number of the conductors in series for one phase in a three-phase motor is :

$$N_3 = \frac{E_3 \ 0.97 \ x \ 60}{n \ \phi_3 \ C_3}$$

where

E_3 = nominal voltage

n = syncronous speed

ϕ_3 = magnetic flux

C_3 = winding factor

This winding factor varies but little, we may take its value at :

$C_3 = 0.665$

In the single-phase motor the number of conductors

conductors in series is :

$$N_1 = \frac{E_1 \quad 0.95 \times 54}{n \, \phi_1 \quad C_1}$$

where the winding-factor C_1 varies according to the design of the winding and it may be taken to be = 0.51

Assuming the single-phase motor connected between phase and neutral, and the three-phase motor delta connected, then:

$$E_3 = \sqrt{3} \; E_1$$

As the cross section of the magnetic circuit of the single-phase motor will generally be greater than that of the three-phase motor, we may take :

$$\phi_1 = 1.8 \; \phi_3$$

Assuming for the three-phase motor the efficiency and power factor of 87% and 88% respectively, and for the single--phase motor 80% and 70%, we have

$$\frac{I_1}{I_3} = 7.1$$

The N_1 conductors of the single-phase motor occupy approximately 64% of the total space for the slots; while the N_3 conductors of one phase of the three-phase motor occupy 33% of the total slot space; calling A_1 and A_3 the areas necessary for each conductor, in the single-phase and in the three-phase motor, respectively Aq_1 and Aq_3 the total slot areas required, we will have

$$\frac{Aq_1}{Aq_3} = \frac{0,33 \; N_1 \; A_1}{0,64 \; N_3 \; A_3}$$

For the same current density the ratio between the areas A_1 and A_3 is equal to the ratio between the currents I_1 and I_3; let the totalarea of the slots be the same fraction of the cross section between the inner and outer circles of diameters Do_3 and Di_3 in the three-phase, and Do_1 and Di_1 in the single--phase motor; we have then the relation :

$$\frac{Do_1^2 - Di_1^2}{Do_3^2 - Di_3^2} = \frac{Aq_1}{Aq_3} = 1.34$$

Assuming the same ratio between the inner and outer diameters of the stator, for both motors, we have :

$$\frac{Do_1}{Do_3} = 1.16$$

As we took the same magnetic induction, and the ratio 1.8 between the fluxes, this should be the ratio between the areas of the cross section of the magnetic circuits; calling L_1 and L_3 the axial length of the single-phase and three-phase motors, we have :

$$\frac{\pi \, Do_1 \, L_1}{\pi \, Do_3 \, L_3} = 1.8; \qquad \frac{L_1 \, Do_1^2}{L_3 \, Do_3^2} = 2.1$$

The number of conductors in the stator of the three-phase motor is $3 \, N_3$; for the same current density, the ratio between the weight of copper of the stator for the two motors, per unity of length, will be :

$$\frac{3 \, N_3}{N_1} = \frac{I_3}{I_1} = \frac{3 \times 2.73}{7.1} = 1.15$$

Calling $N_{1\,A}$ the number of conductors of the auxiliary phase of the single-phase motor, we will have, as a representative value:

$$\frac{N_{1\,A}}{N_1} = 0.8$$

Considering the ratio between sections of the conductors used in the main and auxiliary phase, the ratio of the weights of copper of the two windings will be :

$$\frac{N_{1\,A}}{N_1} \times \frac{1}{4} = 0.2$$

Therefore, the ratio between the weights of conductors of the stator per unit of axial length for the two motors, single-phase and three-phase will be :

$$\frac{P_{cu\ S\ 1}}{P_{cu\ S\ 3}} = \frac{1.2}{1.15} = 1.05$$

The ratio between the total section of the rotor conductors for both motors is the same as that of the stator conductors, without the auxiliary phase.

Thus, the ratio between the cost of the conductors of the two motors is approximately the same as the ratio between the respective lengths.

Besides these elements of comparison, we have to consider the equipment and arrangement necessary for the starting up.

The single-phase motor needs an automatic mechanism in order to disconnect the auxiliary phase at about 75% of the nominal speed.

Let us assume the same distribution of equipment costs as we have used in the analysis for the circuit breakers, and suppose that the iron and the conductors have the same influence on the cost accounting caming up 80% of the total material, the cost of insulation etc., being also in the same proportion as the respective volume; admitting also, that the automatic starting mechanism and the capacitor represent together 5% of the cost of material (a low value in any case). Thus, taking the cost of the single-phase motor as unit, we have :

	Single-phase	Three-phase
Conductors	0.4 x 45%	11.6%
Iron and insulation	0.55 x 45%	11.8%
Automatic and capacitor	0.05 x 45%	--
Wages	30%	15.6%
General expenses	10%	5.2%
Interest of investment	15%	7.8%
	100%	52.0%

As a final result, we see that the single-phase motor costs about twice as much as three-phase. This is further increased by the cost of the installation including the conductors, equipments and the devices for the limitation of the starting current.

It was shown that, for the same power, the three-phase circuit breaker costs only 90% of the price of the single-phase; here the difference is still greater, because, in spite of the fact that the capacity of the motors is the same, the power factor and efficiency of the single-phase motor are lower.

4. Influence regarding country development

The use of single-phase motors up to 1 H.P. (fractional horse power motors) is due principally to four factors :

- the fact that the employment of electrical machinery saves time and money;

- the convenience of using the initial distribution networks, which were designed for illumination service with incandescent lamps;

- the not too correct concept (originated 50 years ago) from the supposition that these small loads have no effect on the technical aspects of production, transmission and distribution of power;

the sufficiently good electrical characteristics, justifying the use of single-phase motors, when the existing installation is single-phase.

Of course, even in the present days, it would not be easy to justify the non-employment of these small motors, since they are already found everywhere as apparatus of domestic use.

Meanwhile, as we made clear above, the most advantageous aspect of the employment of three-phase motors is its favourable repercution on the electrical energy producing and distributing system, which is thereby used to the best advantage.

This important fact, is well born out by the discriminating tariffs, adopted by all supply companies, penalising in some measure, the single-phase loads which cause undesirable unbalanced loading conditions on the universally used three-phase transmission distribution systems.

Generators with special characteristics and equipped with damper-windings are generally employed to attenuate the effects resulting from unbalance. In some cases, of heavy unbalance, it will be necessary to employ generators, of low power factor such as 0.7 or 0.6. This results in a much higher cost for the generator and even then, the necessity for phase balancers may arise.

Rural Distribution is apt to be considered in a way a "necessary evil" at least from the point of view of the supply authorities, this because of its low rentability due to the low density of power consumption per km or km2 of area served.

It is therefore imperative to provide facilities for its utmost expansion, and not to limit its use by the small load capacity of inevitably expensive single-phase lines.

Thus, we conclude that for all the above reasons, the use of the single-phase lines should not be encouraged, preference being always given to three-phase distribution systems.

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